Enhancing the dimensional accuracy of a low-cost 3D printer

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**Introduction**

- 3D printing is widely used in the entertainment industry to easily and fast fabricate characters or objects that are first virtually modelled through Computer Graphics.

- Using 3d prints in stop-motion animation, the creators do not have to mold every single facial expression of every character to be swapped from frame to frame.
Introduction

• Recently a great number of low-cost 3D printers have been developed worldwide.

• There is the need to quantitatively compare the performances of different systems.

• Owing to the lack of an international standard guideline, the performance is evaluated upon the dimensional and geometric accuracy of manufactured parts.

• Thus several reference artifacts with different geometries were defined and proposed in the literature to be used for benchmarking.
Other reference parts

Gargiulo (1992)
Iuliano (1994)

Childs (1994)

Xu (2000)

Mahesh (2004)

Kruth (2005)

Castillo (2005)
Other reference parts

Moylan (2014)

Sanchez (2014)

Scaravetti (2008)
Benchmarking

• Most of the proposed artifacts present several different geometries that have similar sizes.

• When dealing with the part’s dimensional accuracy and tolerances, it is particularly convenient to refer to the ISO standard IT grades (ISO-286).

• Nevertheless only a few works in the literature use the IT grades to summarize the results of a benchmarking study.

• An innovative reference part is proposed in for benchmarking purposes.

• The guidelines that were defined by Moylan et al. are kept into account in the definition of the reference part’s geometry.
Guidelines

The following indications are available in the literature:

• have a considerable number of small, medium and large features;

• not consume a large quantity of material;

• have many features of a ‘real’ part;

• have simple geometrical shapes;

• allow repeatability measurements;

• require no post-treatment or manual intervention (no support structures);

• not take long to build.
The proposed reference part

- Includes a higher number of features or dimensions for each range of basic sizes with respect to other benchmarking artifacts that have been proposed in the literature;

- Includes several classic geometries;

- Geometric features appear both in the concave and convex shapes;

- Does not require support structures for its production, allowing for manufacturing on 3D printers that come with a unique extruder.

Replicas of the reference part are printed out of ABS (acrylonitrile butadiene styrene) material by means of the compared machines using different layer thickness.
Features of the reference part

- a set of seven rectangular blocks (BL)

Overall dimensions
110 x 110 x 33 mm
Features of the reference part

• a set of seven rectangular blocks (BL)
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- a set of seven rectangular blocks (BL)
- a set of seven rectangular slots (SL)
- a set of seven steps (ST)
- two couples of coaxial truncated cones (TC1 and TC2)
- two sets of coaxial cylinders (CC1 and CC2)
- two sets of horizontal cylinders (HC1 and HC2)
- four sets of quarters of spheres (SP1, SP2, SP3, SP4)
- three sets of tilted planes (TP1, TP2, TP3)
- several other vertical or horizontal planes, that are parallel or orthogonal to the square base of the reference part.
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**Overall dimensions**

110 x 110 x 33 mm
COMAU at a glance

A name that means tradition, competence and great experience.

Comau originally got its name from the abbreviation of COnsorzio MAchine Utensili and now with 40 years of experience in advanced manufacturing systems, it represents a proven world-wide leader in sustainable automation and service solutions with a forward focus.

Today, Comau has a truly global presence, with 24 locations in 13 countries, which allows us to offer tailor-made solutions and localized support in a variety of fields (automotive, aerospace, petrochemical, military, shipbuilding and energy efficiency consultancy).
Specializing Master in Industrial Automation

The task of enhancing the performances of the 3D printer Prusa i3, that is supplied in the assembly box, was assigned to 16 engineers attending the Master who were divided into 4 groups.

In order to assess and validate the improvements, a benchmarking activity was carried out to evaluate the dimensional accuracy of the 4 modified printers.
Compared printers
List of main improvements:

- anti-vibration feet
- Z axis holder
- Y axis end course riser
- bed adjust striped nuts
- power supply holder
- double fan duct
- spool rotating holder
- filament guide
- extruder gears
Fluo

List of main improvements:

• Y axis endstop leverage
• filament holder
• Y axis chain
• X axis chain
• fan protection grid
• adjustable heated bed device
• filament guide +z axis ending
Metallica

List of main improvements:

• motor protection
• fan guard
• catenary
• extruder holder
• X-axis and Y-axis belt tensioner
• X-axis and Y-axis carriage
• power supply cover
• spool holder
• bed leveling knob
• anti-wobble
List of main improvements:

• Z axis support
• filament guide
• spool holder
• stiffener rods
• X axis chain
• auto bed leveling kit
• bowden kit
• auto bed leveling kit
The manufactured replicas

- **Ghostprinters**
  - Nozzle size: 0.20 mm
  - Layer thickness: 0.15 mm
  - Printing time: 9.5 hours

- **Fluo**
  - Nozzle size: 0.40 mm
  - Layer thickness: 0.20 mm
  - Printing time: 5.5 hours

- **Metallica**
  - Nozzle size: 0.30 mm
  - Layer thickness: 0.20 mm
  - Printing time: 6 hours

- **Print-Doh**
  - Nozzle size: 0.40 mm
  - Layer thickness: 0.25 mm
  - Printing time: 5 hours
**Dimensional inspection**

The CMM machine declared volumetric length measuring uncertainty $MPE_E$ according to ISO-10360/2 is

$$1.5 + \frac{L}{333} \mu m$$

Three replications were made for the inspection of each part.

At least 10 inspection points were measured on each geometric feature.

A unique configuration of the CMM probe with the axis orthogonal to the part base plane is required.
ISO 286 Guideline

The dimensional quality of a part is defined by IT grades.

For each range basic size, the IT grade is related to the maximum admitted deviation with respect to the nominal dimension.

<table>
<thead>
<tr>
<th>Basic size mm</th>
<th>Up to and including</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 \textsuperscript{3)}</td>
</tr>
<tr>
<td>3</td>
<td>0,8 1,2 2 3 4 6 10 14 25 40 60</td>
</tr>
<tr>
<td>6</td>
<td>0,12 0,18 0,3 0,48 0,75 1,2 1,8</td>
</tr>
<tr>
<td>10</td>
<td>0,15 0,22 0,36 0,58 0,9 1,5 2,2</td>
</tr>
<tr>
<td>18</td>
<td>0,18 0,27 0,43 0,7 1,1 1,8 2,7</td>
</tr>
<tr>
<td>30</td>
<td>0,21 0,33 0,52 0,84 1,3 2,1 3,3</td>
</tr>
<tr>
<td>50</td>
<td>0,25 0,39 0,62 1 1,6 2,5 3,9</td>
</tr>
<tr>
<td>80</td>
<td>0,3 0,46 0,74 1,2 1,9 3 4,6</td>
</tr>
<tr>
<td>120</td>
<td>0,35 0,54 0,87 1,4 2,2 3,5 5,4</td>
</tr>
</tbody>
</table>

\textsuperscript{1)} Numerical values of standard tolerance grades IT for basic sizes up to 3 150 mm.
**Standard tolerance factor**

The values of standard tolerances corresponding to IT 5 – IT 18 grades for nominal sizes up to 500 mm are evaluated through the standard tolerance factor $i$ that is expressed in micrometres by the following formula:

$$i = 0.45 \cdot 3\sqrt[3]{D} + 0.001 \cdot D$$

Where $D$ is the geometric average of the range of nominal sizes in millimeters:

$$D = \sqrt[3]{D_1 \cdot D_2}$$

<table>
<thead>
<tr>
<th>Range</th>
<th>Basic sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Above</td>
</tr>
<tr>
<td>$D_1$ (mm)</td>
<td>1  3  6  10  18  30  50  80</td>
</tr>
<tr>
<td>Standard tolerance factor $i$ ($\mu$m)</td>
<td>0.542  0.733  0.898  1.083  1.307  1.561  1.856  2.173</td>
</tr>
</tbody>
</table>
ISO IT grades

The IT grades are classified by the number $n$ of times that the tolerance factor $i$ fits into the dimensional deviation.

For a generic nominal dimension $D_{jn}$, the number $n_j$ of tolerance units is computed as follows:

$$n_j = \frac{1000 |D_{jn} - D_{jm}|}{i}$$

where $D_{jm}$ is the corresponding measured dimension.

<table>
<thead>
<tr>
<th>Basic size</th>
<th>Standard tolerance grades</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>Up to IT 5 IT 6 IT 7 IT 8 IT 9 IT 10 IT 11 IT 12 IT 13 IT 14 IT 15 IT 16 IT 17 IT 18</td>
</tr>
<tr>
<td>1 mm 500 mm</td>
<td>7i 10i 16i 25i 40i 64i 100i 160i 250i 400i 640i 1000i 1600i 2500i</td>
</tr>
</tbody>
</table>

In this study, the $n$ value corresponding to the 95th percentile of the distribution within each range is assumed as the maximum dimensional error.
Distribution of $n$ for different ISO ranges

Confidence level is set to 95%
Comparison of results
Comparison of results

Part quality ranges from IT11 to IT16.

Smaller features have lower dimensional accuracy.

<table>
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<tr>
<th>Basic size mm</th>
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<tr>
<td></td>
<td>0,8 1,2 2 3 4 6 10 14 25 40 60</td>
<td>μm</td>
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<td>3</td>
<td>6 1 1,5 2,5 4 5 8 12 18 30 48 75</td>
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<td>6</td>
<td>10 1 1,5 2,5 4 6 9 15 22 36 58 90</td>
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<tr>
<td>10</td>
<td>18 1,2 2 3 5 8 11 18 27 43 70 110</td>
<td>0,18 0,27 0,43 0,7 1,1</td>
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<tr>
<td>18</td>
<td>30 1,5 2,5 4 5 9 13 21 33 52 84 130</td>
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<tr>
<td>30</td>
<td>50 1,5 2,5 4 7 11 16 25 39 62 100 160</td>
<td>0,25 0,39 0,62 1 1,6</td>
</tr>
<tr>
<td>50</td>
<td>80 2 3 5 8 13 19 30 46 74 120 190</td>
<td>0,3 0,46 0,74 1,2 1,9</td>
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<tr>
<td>80</td>
<td>120 2,5 4 6 10 15 22 35 54 87 140 220</td>
<td>0,35 0,54 0,87 1,4 2,2</td>
</tr>
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**Table 1 — Numerical values of standard tolerance grades IT for basic sizes up to 3 150 mm**

1. **IT1** to **IT18**.
Form error

Average form error (mm)

- **METALLICA**
- **FLUO**
- **GHOSTPRINTERS**
- **PRINT-DOH**

**Graph Description:**
- **SPHERES**
  - Convex: Low error
  - Concave: Low error
- **HORIZONTAL CYLINDERS**
  - Convex: Low error
  - Concave: Low error
- **VERTICAL CYLINDERS**
  - Convex: Moderate error
  - Concave: Moderate error
- **CONES**
  - Convex: High error
  - Concave: High error
Flatness

Flatness TP

Flatness VP

Maximum range for HP
Flatness

Flatness HP

Parallelism

Dev (mm)

Metallica  Ghostprinters  Fluo  Print-Doh
Angular errors

Horizontal Planes

Vertical Planes

Tilted Planes
Conclusions

• Greater geometric accuracy for the Ghostprinters and Print-Doh devices. However

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• The difference in the performance can be ascribed to the improvements, but also to the optimized printing parameters.

• Over the first benchmarking results presented, the reference part will be used for comparing other FDM machines by fabrication of new replicas.

• The proposed methodology has a general applicability and could also be extended to other AM systems that are used for production of metal parts.
Enhancing the dimensional accuracy of a low-cost 3D printer

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Thanks for your attention!